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# MECHANICAL PROPERTIES OF COLLAGEN FIBER AGGREGATES FROM STEERHIDE


## ABSTRACT

Techniques are described for measuring mechanical properties of collagen fiber aggregates removed from untanned and tanned samples of the belly portion of a steerhide. Results of measurements of mechanical properties such as Hookean modulus, ultimate tenacity, ultimate strain, hysteresis, and permanent set are reported, and tenacity-strain curves are presented. The effects upon the various properties of varying gage length and linear density of the fiber aggregates are considered.

The form of the tenacity-strain curves on wet and dry samples indicated the expected plasticizing effect of sorbed water. Curves for the untanned aggregates, especially under dry conditions, exhibited behavior in the low-strain region which may be interpreted as the straightening and alignment of the "primitive fibers" into the direction of stress. Tanning appeared to inhibit this process in that the tenacity-strain curves rose more abruptly from the origin. At higher strains, the tanned aggregates yielded more rapidly, suggesting that the restraint imposed by tanning upon fiber readjustment had broken down. Tanning also was found to improve resilience, as indicated by lower values of the dissipative properties in cycling experiments.


—x—x—

## INTRODUCTION

The utility of leather derives mainly from its unique physical properties, which are usually determined by conventional tensile, tearing, and bursting tests. These physical properties can be expected to bear some relationship


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to the fundamental properties of the individual components of leather and the arrangement of these components in the leather. However, because of the scarcity of observations on these two factors the relationship of the conventionally measured properties of leather to the fundamental properties of the components remains poorly defined. Thus, it would be highly desirable to develop appropriate tests for the collagen fibers constituting a hide, which might serve to predict hide properties. This would also help to relate the properties of collagen fibers to the properties of other fibers of natural and synthetic origin for which the data are abundant.

It is now recognized that the corium of animal skin is made up of a mesh of collagen fiber aggregates, ranging from 20 to 200$\mu$ in diameter, which can be broken down into "primitive fibers" of the order of 10$\mu$ in diameter. These, in turn, can be divided by ultrasonic vibrations into "fibrils", ranging from 0.5$\mu$ to 0.001$\mu$ in diameter, which can be still further divided into "filaments" (1). It is difficult to extract a single primitive fiber of reasonable length from a hide or leather, and for the most part, aggregates of primitive fibers are the smallest units available for mechanical measurements with conventional testing equipment.

Several studies of the mechanical properties of collagen fiber aggregates have been made. Mitton (2) reported in 1945 results of measurements of tensile strength, rigidity, regain, and extensibility of collagen fiber aggregates from the belly area of a vegetable-tanned commercial steerhide. The following year Conabere and Hall (3) evaluated Young's modulus and permanent set of fiber aggregates teased from both chrome-tanned and vegetable-tanned belly portions of oxhides. Later Roddy (4) characterized the effect of sodium sulfide on the strength of collagen fiber aggregates by changes in their "mean breaking length." These measurements were made on several areas of fresh, chrome-tanned, and vegetable-tanned hides.

In 1960, Morgan and Mitton (5,6) and Morgan (7,8) reported extensive statistical studies of the mechanical properties of both raw and vegetable-tanned collagen fiber aggregates. In their experiments, the fiber aggregates were all taken from the same cowhide, and the tanning was done on the free fiber aggregates.

The work discussed in this paper consisted of an intensive study of the mechanical properties of collagen fiber aggregates taken from tanned and untanned belly portions of a single steerhide. This work was preliminary to a more extensive study in which measurements of fiber aggregate properties and hide characteristics of various regions of several steerhides, tanned and untanned, were made and analyzed. Significant findings of this broader program will be treated in a future paper.

Definitions of terms and units employed by textile technologists but not commonly used by leather chemists are given in the Appendix.

## PREPARATION OF HIDE SAMPLES

A steerhide, referred to as "Hide A," was treated as follows: After removal of the flesh and grain splits from the soaked, limed, and bated hide, the remaining center split was divided into halves by a cut along the backbone. One half was tanned with vegetable (natural organic) tannins with a regular pack, fatliquored, set out, and dried. The other half was acidified to pH 5.5, dehydrated with acetone, and dried, while tacked to the same pattern used for the tanned half. The chemical analysis of a sample from the tanned half is given in Table I.

TABLE I

CHEMICAL ANALYSIS OF TANNED HIDE A

| | Percent |
|---|---|
| Moisture | 10.92 |
| Petroleum ether extract | 7.78 |
| Insoluble ash | 0.15 |
| Hide substance | 44.74 |
| Soluble nontannin | 3.58 |
| Uncombined tannin | 5.51 |
| Combined tannin | 27.32 |
| Total | 100.00 |
| Water-soluble material | 9.09 |
| Total ash | 2.07* |
| Glucose | none |
| $Cr_2O_3$ | none |
| pH | 4.88 |
| Degree of tannage | 61.08 |
| $T_s$ (Theis meter) | 85°C. |

Analysis was done on "as is" basis by methods of the American Leather Chemists Association.
*Necessary to use $HNO_3$ to burn off carbon.

## EXPERIMENTAL PROCEDURES

*Removal of fiber aggregates from hide.*—In accord with experience of previous investigators (5, 6, 7), it was found to be impossible to isolate single primitive fibers of reasonable length from either the untanned or the tanned hide. Thus, it was decided to use fiber aggregates which could be removed with minimum apparent fiber damage and of adequate length for testing. Two methods for obtaining fiber aggregates were investigated, microdissection and removal with tweezers.

In employing the microdissection technique, the hide sample was fastened to a frame and observed under a low-power binocular microscope. Each fiber aggregate was pulled individually from the hide mesh with fine tweezers and round-tipped needles, and other fiber aggregates which impeded its removal were cut off with scissors. After removal of several aggregates, the working area of the hide became fuzzy. This method was laborious and slow. Since only short fiber aggregates could be removed without damage, the microdissection technique was abandoned.

The tweezer technique was employed as follows: Using a jeweler's lens, the end of a fiber aggregate was selected at the edge of the hide sample. The aggregate was then grasped with tweezer tongs (a special type of eyebrow tweezers) and gently pulled out. Many aggregates broke, but as the hide mesh opened up, long undamaged aggregates could be obtained. An experienced operator could judge the quality of a fiber aggregate by the ease with which it could be extracted from the mesh.

The tweezer technique was applied under three conditions: (*a*) wet hides frozen in liquid air and then brought to room temperature, (*b*) wet hides frozen to microtome bed cooled with solid $CO_2$ and sliced, and (*c*) hides dry under room conditions. After considerable experimentation, it was found that the simple tweezer technique under condition (*c*) was best, and it was employed in all cases. A skilled operator can extract usable aggregates as long as 25 mm. from the back and shoulder regions of the untanned hides; considerably longer aggregates can be extracted from the less compact belly region (50 mm.). All aggregates thus removed were examined microscopically, and the longer undamaged samples were chosen for the mechanical tests. Photomicrographs of fiber aggregates tested and constituent primitive fibers are shown in Fig. 1. In certain experiments to be described later, the length and thickness were controlled by careful selection.

*Measurement of fiber aggregate dimensions.*—The fiber aggregates were fastened to small plastic tabs either with epoxy resin or with a small amount of cellulose cement which was covered with glyptal enamel. About 10 mm. of each fiber aggregate was thus "wasted" on the tabs. The gage length (free length between tabs) was measured with a traveling microscope.

The vibroscopic method (9) is now commonly used for the measurement of the linear density (mass per unit length) of textile fibers. Attempts to apply this technique to the collagen fiber aggregates were unsuccessful, however, because of their asymmetry of cross section and stiffness which necessitated making a rather large "stiffness correction" (10, 11). Thus, the weight of the tested length of the fiber aggregates was measured at 65% relative humidity and 70°F. with a quartz torsion ultramicrobalance* having a sensitivity of 0.05 micrograms, which was very stable and rapid in opera-

*Model E, Microtech Services Co.

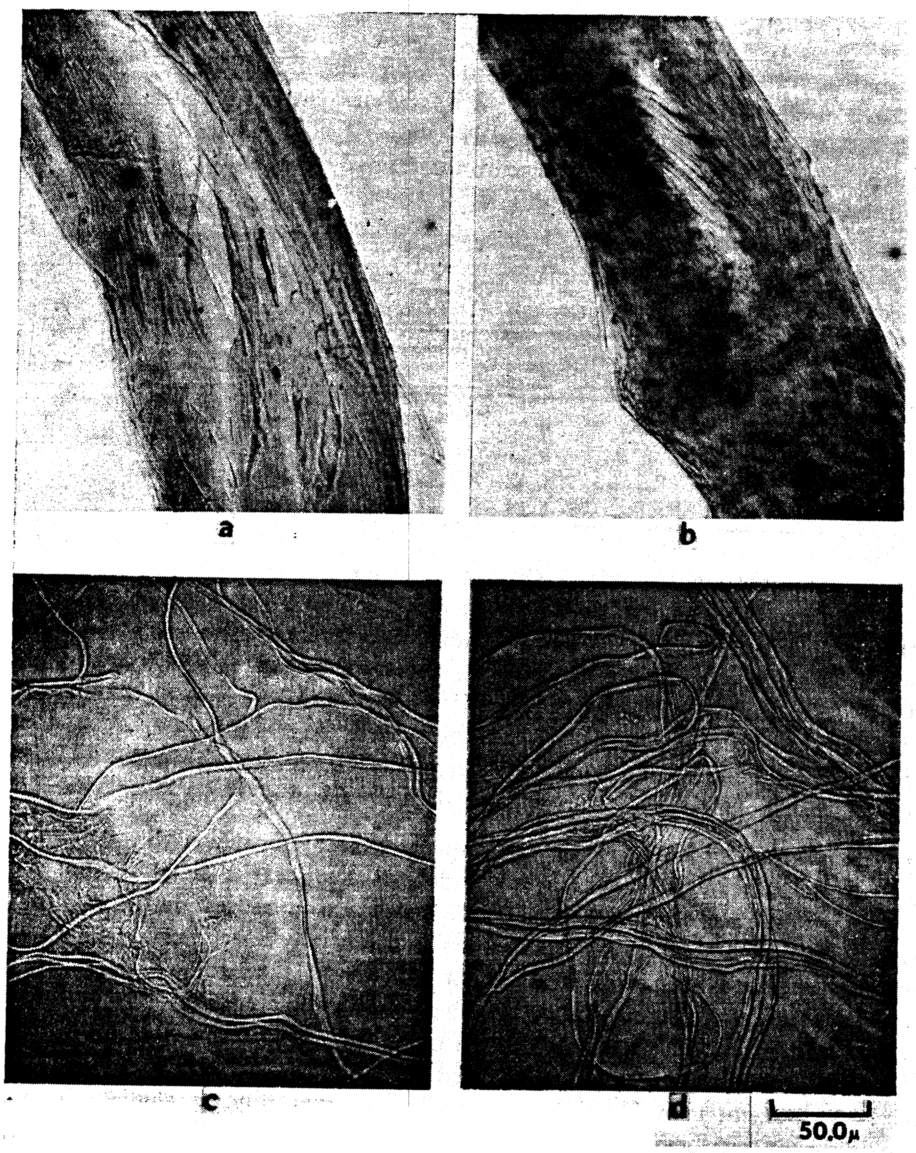


FIGURE 1.—Photomicrographs of collagen samples.

*a.* Untanned collagen fiber aggregate.
*b.* Tanned collagen fiber aggregate.
*c.* "Primitive fibers" from untanned aggregate.
*d.* "Primitive fibers" from tanned aggregate.

tion. The linear density was reduced to the internationally recommended tex units, i.e., grams weight per kilometer length (micrograms per millimeter). It should be remarked that the linear density values, measured under the "dry" conditions of 65% R.H. and 70°F., were not corrected for moisture pickup, in normalizing the tensile loads to "tenacities" (load/linear density) measured under wet conditions, i.e., with samples submerged in water. Quotes are used around *dry* to indicate that although these fibers are dry to the touch, they still contain 14% moisture for tanned fibers and 20% moisture for untanned fibers as shown in Table II.

## TABLE II

MOISTURE SORPTION OF HIDE A

| Relative Humidity | Relative Weight Tanned Sample | Relative Weight Untanned Sample |
|---|---|---|
| 0 (bone-dry) | 1.000 | 1.000 |
| 65% (adsorption) | 1.16 | 1.25 |
| 100% | 1.42 | 1.60 |
| 65% (desorption) | 1.18 | 1.26 |

The argument is sometimes advanced that, in comparing properties of fibers with varying moisture content, the linear densities should be corrected to include the sorbed water, at the relative humidity in question. In these experiments, however, it was desired to compare these quantities at 65% R.H. and 100% R.H., and there seemed to be little point in converting linear density values (measured at 65% R.H.) to bone-dry values, thus introducing a constant factor in all modulus and tenacity values. For those who wish to make such corrections, however, moisture sorption data are given in Table II.

*Tensile measurements.*—All load-strain measurements were performed with an Instron testing machine. This device is now widely used for textile fibers. It operates at constant rate of crosshead travel. Loads are measured and recorded with a resistance strain gage unit which is essentially inertialess. The machine was operated in a room maintained at 65% R.H. and 70°F. Wet tests were made with collagen aggregates suspended in water buffered to pH 4.6. Loads in grams for various measured extensions and at rupture were read from the recorder charts and converted into tenacity units, i.e., grams/tex. The Hookean modulus was calculated from the slope of the linear portion of the tenacity-strain curve in units of grams/tex for unit strain.

The rate of crosshead travel was 0.254 cm/min for all measurements used to plot the tenacity-strain curves and for calculations of modulus, ultimate tenacity, and rupture strain. For cycling tests in which the samples were both extended and retracted, the rate of crosshead travel was 0.127cm/min. It should be noted that the rate of strain depends upon fiber aggregate gage length. Thus, for those experiments where gage length was not controlled, the rate of strain varied also. The effects upon the tensile properties of varying gage length, rate of strain, and linear density will be discussed later.

## EFFECTS OF VARYING GAGE LENGTH AND LINEAR DENSITY

For single fibers which are radially homogeneous it is well known that the breaking strength (ultimate tenacity) is a function of the gage length and the rate of strain. In general, ultimate tenacity decreases with increasing gage length and decreasing rate of strain. For the small variations of rate of strain of these experiments, the effects of this parameter are negligible. The ultimate tenacity is usually independent of the cross-sectional area and the linear density. For single fibers which are not radially homogeneous, such as wool or cotton (12, 13), the ultimate tenacity sometimes varies with the linear density, other parameters being held constant. Thus, great care must be observed when measured tensile forces are converted to stresses or tenacities. A collagen fiber aggregate presents an even more complicated situation. It is a bundle composed of several primitive fibers which are not necessarily parallel or linearly disposed to the axis of the aggregate. Indeed, there may be a heterogeneous bonding material between the primitive fibers which could profoundly affect their relative movement when a tensile force is applied to the aggregate. Thus, caution in extrapolating from single-fiber behavior to that of the collagen fiber aggregate is indicated. In this connection, Morgan and Mitton (5) have shown for raw collagen fiber aggregates from cowhide that "breaking length" in kilometers (equivalent to ultimate tenacity in grams/tex, used in this paper) decreases with increasing gage length and also decreases with increasing linear density. A similar dependence of "breaking length" upon linear density for vegetable-tanned collagen fiber aggregates was found by Mitton and Morgan (6).

In view of the much narrower range of experimental conditions employed in this work (as compared to those of Morgan and Mitton [5] and Mitton and Morgan [6]), it seemed necessary to make further studies of the effects of gage length and linear density upon the tensile properties. Results of an experiment performed on tanned fiber aggregates at 65% R.H. and 70°F. are plotted as bar graphs in Fig. 2. The fiber aggregates employed in this experiment were carefully selected to fit two of four principal descriptions: "long" (2 cm.), "short" (1 cm.), "thick" (8.3 to 8.8 tex), and "thin" (5.4 to 5.8 tex). An additional group of "very thin" (0.47 tex) fiber aggregates was tested, but only at the short gage length.

The effects of linear density upon Hookean modulus, ultimate tenacity, and ultimate strain are shown in the modified bar graph of Fig. 2. Each bar represents the mean of measurements on 36–40 fiber aggregates. The triangular patterns at the peaks of the bars represent 95% confidence limits. Figures given at the base of each bar are coefficients of variation.

It should be noted that the modulus (slope of the linear portion of the tenacity-strain curve) is essentially independent of linear density. Modulus is clearly a low variance property, except for the very thin aggregates. A

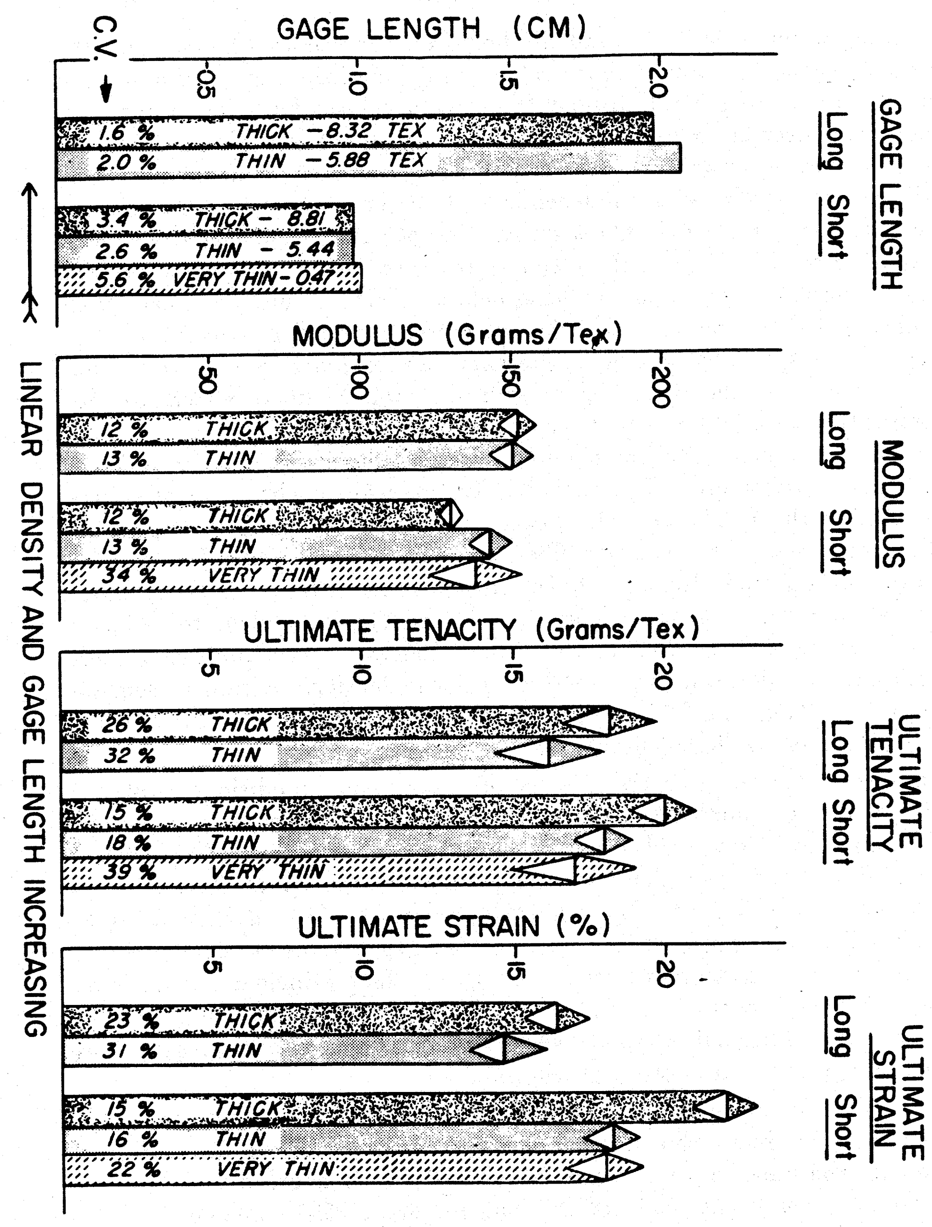


FIGURE 2.—Effects of varying linear density and gage length.

Each test made on 36 to 40 fibers from tanned sample at 65% R.H., 70°F. Crosshead speed = 0.254 cm/min. Triangular patterns at peaks measure 95% confidence limits.

tendency for ultimate tenacity and ultimate strain to fall off with decreasing linear density is apparent and may be significant. However, calculated correlation and regression coefficients for the individual data making up the means of Fig. 2 indicate a slight negative dependence of ultimate tenacity upon linear density, in agreement with earlier findings (5, 6).

The effects of varying the gage length by a factor of 2 are shown in the bar graph of Fig. 2. Here it is seen that modulus varies little with gage length for the thin aggregates. Both ultimate tenacity and ultimate strain decrease somewhat with increasing gage length, in accord with textile fiber experience and the results of Morgan and Mitton (5) for raw fiber aggregates. The dependence of ultimate tenacity upon gage length is rather small, however, considering the 2/1 variation in mean gage length.

In regard to variability, there is nothing to remark except that it is somewhat higher for long fiber and the very thin fiber (low-linear-density) aggregates. As previously mentioned, the variability of modulus is relatively low, but this is in accord with experience with all types of tensile tests in which stiffness is found to be more accurately measurable than are the rupture properties.

The results of these experiments serve to establish bases for interpretation of subsequent data for which gage length was not controlled and linear density varied appreciably. Obviously, it would have been desirable to perform similar experiments on tanned wet samples and on untanned samples, wet and "dry," but it is reasonable to assume that the results on tanned "dry" samples will translate to the more general situation. It should be noted also that the experiments on the effects of gage length actually include the effects of rate of strain, since the rate of crosshead travel was constant. Strictly speaking, the measured effects of varying gage length should be described as the effects of simultaneous variation of gage length and rate of strain. Fortunately, for the range of parameters selected, these effects are not large.

## DERIVED MECHANICAL PROPERTIES

Data on collagen fiber aggregates from tanned and untanned samples of Hide A, wet and "dry," are given in the bar graph of Fig. 3. Coefficients of variation and 95% confidence limits are indicated in the same manner as in Fig. 2.

It will be noted that mean gage length varied somewhat in this experiment. However, on the basis of the results of the last section, in which gage length was varied by a factor of 2, this parameter can be ignored in interpreting the modulus, ultimate tenacity, and ultimate strain data. The relatively large variation in linear density between tanned and untanned samples must be taken into account, however.

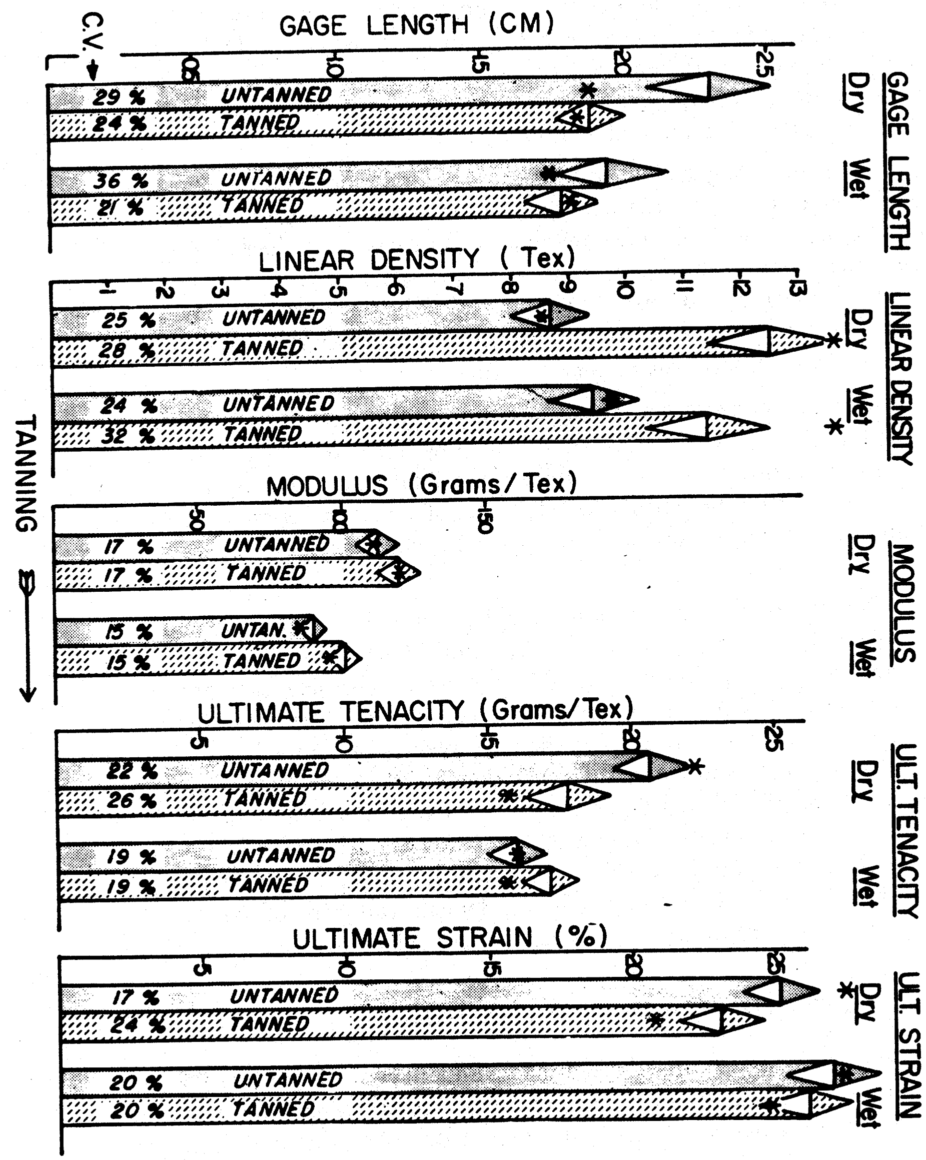


FIGURE 3.—Effects of water sorbed and tanning upon mean properties of aggregates.

Each test made on 40 fibers. Crosshead speed = 0.254 cm/min. Triangular patterns at peaks measure 95% confidence limits. Asterisks indicate ordinates corresponding to data for 15 aggregates selected to have nearly the same gage length.

It seems quite clear from the data of Fig. 3 that sorbed water has the expected plasticizing effect in reducing modulus and ultimate tenacity. Ultimate strain is increased by sorption of water, but not greatly, in view of the observed variance. Tanning has no significant effect upon modulus, but there is a slight indication of a stiffening effect (increasing modulus). Tanning does seem to reduce strength (ultimate tenacity) under "dry" conditions, but there is little effect upon the wet fiber strength, and the effects upon ultimate strain are obscure. The tendency of ultimate tenacity and ultimate strain to increase with increasing linear density of the tanned samples (refer to Fig. 2) makes uncertain the conclusion that ultimate tenacity decreases with tanning (even in the "dry" state) and suggests that the effects of tannage upon ultimate strain are small.

These results indicate no significant difference in variability between wet and "dry" or between tanned and untanned samples. As expected, modulus is a relatively low variance property. It is rather interesting, however, to note the effect of selecting results on 15 of the 40 fiber aggregates on the basis of small variance in gage length. These results are indicated by asterisks in the bar chart of Fig. 3. Clearly, this rather artificial imposition of the condition of constant gage length upon the data has little effect upon the values of the tensile properties obtained from the more accurate 40-aggregate experiment in which gage length was not controlled. However, on the basis of these "constant gage length" tests, it appears that the observed reductions in the "dry" ultimate tenacity and strain resulting from tanning are real.

## TENACITY-STRAIN RELATIONSHIPS

The stress-strain curve is now accepted as a very useful criterion of textile fiber behavior. Ordinarily, however, tensile data are plotted as tenacity (load/linear density) versus tensile strain. When it is desired to convert to stresses, all that is necessary is to multiply tenacities by the specific gravity of the material in question. Unfortunately, the recently published "average stress-strain curve" of Morgan (7) is not a true stress-strain curve. He chose to plot fractions of breaking extensions against corresponding fractions of breaking loads, for a large number of fibers. Such a curve has little meaning, since all points are referred to the high variance rupture condition. Morgan also plots strain against load for fiber aggregates of constant gage length (0.6 cm.) and linear density (100 $\mu g/cm$ = 10 tex). These curves should have the form of stress-strain curves, when ordinates and abscissae are interchanged. However, when load is plotted against strain, none of Morgan's curves exhibits the expected "character" in the low strain region where considerable aligning and straightening of the primitive fibers must take place. His load-strain curves are all of the same general shape, i.e., slightly convex toward the strain axis. Since he does not show the experimental

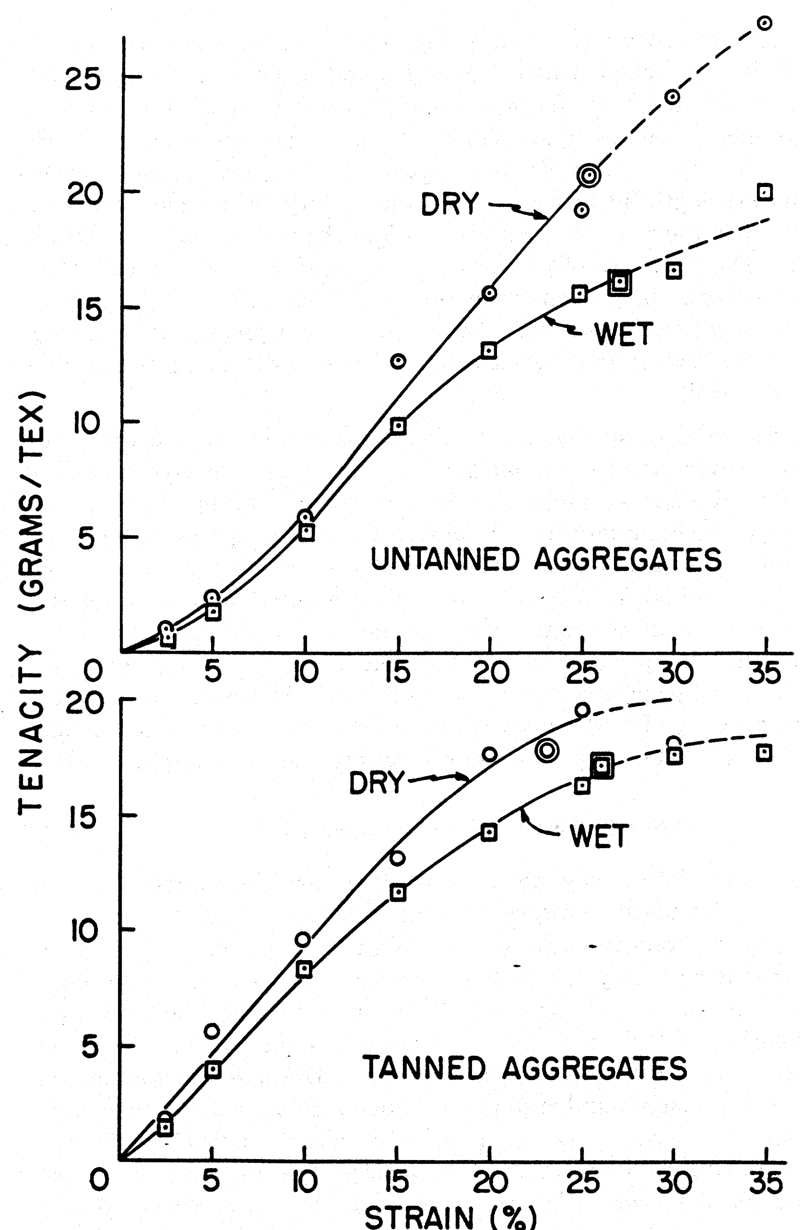


FIGURE 4.—Average tenacity-strain curves. Effects of sorbed water.

Wet fibers immersed in water at pH 4.6.
"Dry" fibers tested in room at 65% R.H., 70°F.
Dashed parts of curves are extensions beyond the doubly enclosed points plotted for the mean values of ultimate tenacity and strain.

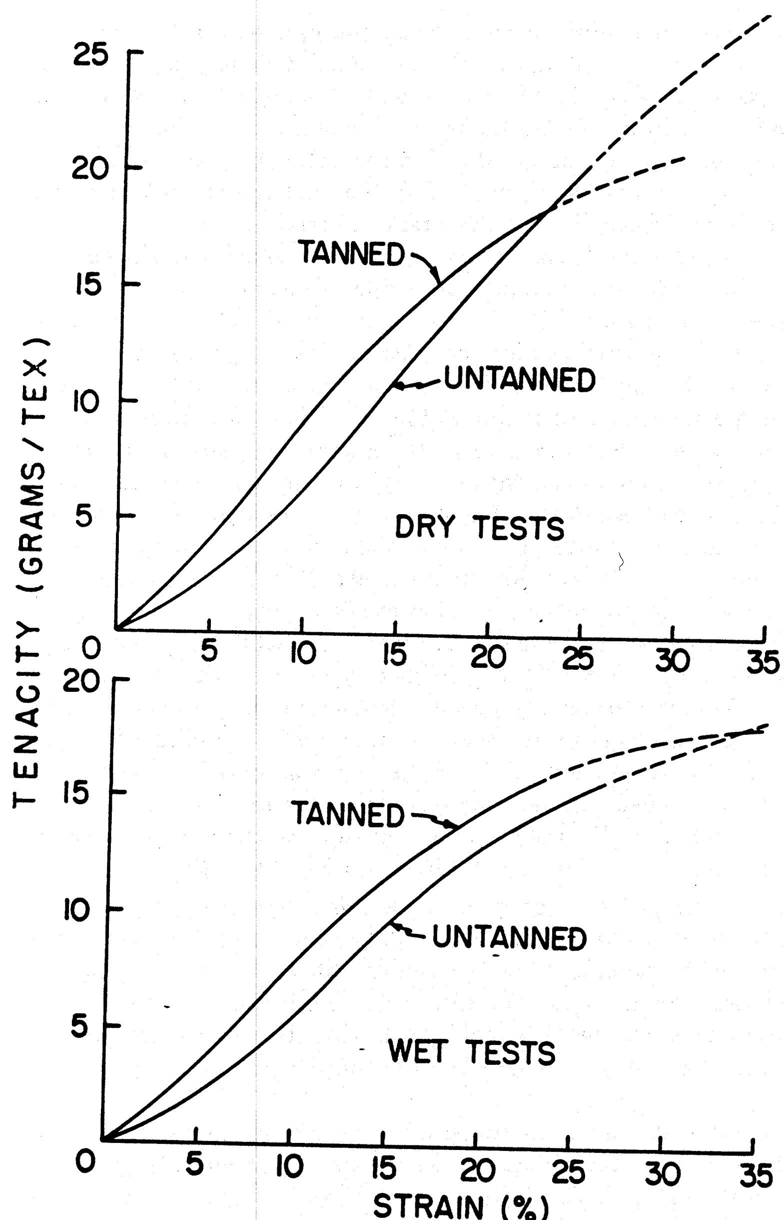


FIGURE 5.—Average tenacity-strain curves. Effects of tanning.

Wet fibers immersed in water buffered to pH 4.6.
"Dry" fibers tested in room at 65% R.H., 70°F.
Dashed parts of curves are extensions beyond the doubly enclosed points plotted for the mean values of ultimate tenacity and strain.

points on the curves, it is difficult to estimate the precision of his measurements in the various regions of strain. It is reasonable to suppose, however, that the extensiometer used (14), which provided a constant rate of loading (3 to 24 g/min) with load measured by the "chain loop" principle, may have been incapable of revealing the detailed nature of the load-strain curve at low strains. The Instron machine used in the experiments of this paper is well designed for studies over the whole range of strains.

The data of Fig. 3 have been plotted as average tenacity-strain curves. This was done in the obvious manner; individual measured ordinates (tenacities) at various strains (0, 5, 10, 15, 20, 25, 30, and 35%) were averaged, and the averages were plotted against those strains, as in Figs. 4 and 5. The dashed portions of the curves extend beyond the points plotted for the mean values of ultimate tenacity and strain of Fig. 3. There is nothing unusual about these curves, although they may be the first tenacity-strain curves for collagen fiber aggregates obtained with modern, precise equipment to appear in the literature. It will be noted in Fig. 4 that sorbed moisture has the usual effect of shifting the curve toward the strain axis, both for the tanned and the untanned specimens. The curves for the untanned, "dry" aggregates have a pronounced concave-upward curvature at low strains, as is found for a crimped wool fiber. This behavior in the low-strain region probably corresponds to a straightening and alignment of the primitive fibers into the direction of tensile stress. As this process approaches completion the untanned aggregates assume briefly a Hookean behavior and then yield, as indicated by the final concave-downward portion of the curve. It was noted for several of the most extensible tanned collagen aggregates that the tenacity-strain curve turned upward again at high strains. This behavior was too rare to influence appreciably the values of the average ordinates in Figs. 4 and 5.

The curves for the tanned aggregates show much less upwardly concave character at low strains and stresses. This could very well reflect some sort of bonding, induced by tanning, between primitive fibers that is strong enough to inhibit the straightening and alignment process but which finally breaks down at higher stresses and permits rapid yield. This behavior is emphasized in Fig. 5, in which curves for tanned and untanned aggregates are directly compared.

If one ignores the difference in shape of the stress-strain curves of this paper and those of Morgan, his results on the effects of moisture sorption and vegetable tanning agree qualitatively with those of Figs. 4 and 5. His work covers a much wider range of parameters such as gage length, linear density, and relative humidity. On the other hand, most of his strain-load curves were obtained with rather short fibers (0.6 cm.) which would introduce variability.

It should be remarked at this point that the problem of length and thickness of fiber aggregates is still present, even taking into account the considerations of the section on varying gage length and linear density. Thus, an attempt was made to perform mechanical tests which would yield quantities independent of fiber aggregate dimensions, as described in the next section.

## CYCLING EXPERIMENTS

In a further effort to compare the properties of tanned and untanned fiber aggregates, the cycling data of Table III were obtained as follows: Aggregates were taken from the belly portion of Hide A and tested at 65% R.H.

### TABLE III

CYCLING DATA

*(Belly portion of Hide A; 65% R.H.; 70°F.; gage length, 2 cm.)*

| Sample | Test Strain % | 1st-Cycle Hysteresis % | Extension Work Chng. % | Set 1–2 % | Set 1–3 % | Ultimate Strain % |
|---|---|---|---|---|---|---|
| Untanned—means | 20 | 39.1 | 24.7 | 4.4 | 5.0 | 22.1 |
| (9 tests) C.V. | | 16.4 | 28.1 | 23.6 | 23.3 | 6.7 |
| Tanned—means | 10 | 24.7 | 15.1 | 1.07 | 1.34 | 19.4 |
| (11 tests) C.V. | | 13.0 | 14.0 | 34.4 | 26.8 | 23.4 |

and 70°F. The gage length (2 cm.) and the rates of extension and contraction (6.3%/min) were maintained constant. The maximum strain for cycling was chosen to bring the fiber aggregates through the Hookean region, i.e., to the point where yield is first apparent in the average tenacity-strain curves of Fig. 4. This "test strain" was found to be 20% for the untanned and 10% for tanned sample.

Each fiber was extended to the appropriate test strain and then immediately retracted at the same rate. After one minute's rest, the aggregate was re-extended, permitting the crosshead to travel as far as in the first cycle, and immediately retracted. After another minute's rest, the fiber was extended to rupture. Five parameters were calculated: (*a*) first-cycle hysteresis—the difference in the work of extension and retraction, expressed as a fraction of the work of extension; (*b*) extension work change—the difference between the work of the first and second extensions, expressed as a fraction of the work of the first extension; (*c, d*) permanent set—unrecovered strain at the start of the second and third extensions, expressed as a fraction of the initial length; (*e*) ultimate strain, expressed as a fraction of the initial length.

It will be noted that all of the dissipative properties measured (hysteresis, extension work change, and set) are much smaller for the tanned sample aggregates. Thus, under these experimental conditions, the fiber aggregates

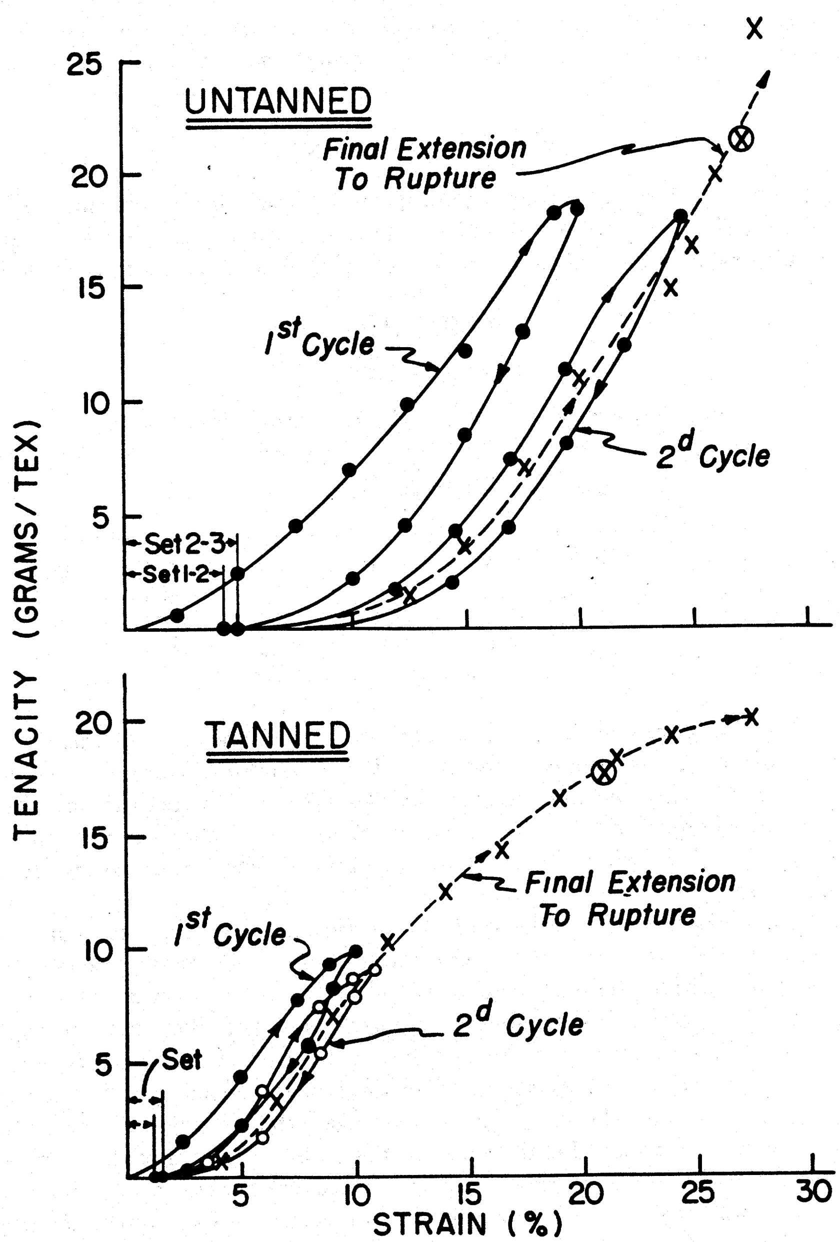


FIGURE 6.—Average tenacity-strain cycling curves.

Belly portion of Hide A; 65% R.H. 70°F.; gage length, 2 cm.

from the tanned sample may be considered to have a higher resilience, in the range of strains from zero to yield. On the basis of the coefficients of variation, the first-cycle hysteresis appears to be a low variance property (comparable to Hookean modulus in this respect). This is not true for the other dissipative properties, however. The cycling data are plotted as tenacity-strain curves in Fig. 6.

## SUMMARY

The results of this work indicated that collagen fiber aggregates of reasonable length can be removed without serious damage from vegetable-tanned and untanned samples of steerhide and may be tested, either "dry" (65% R.H.) or wet (under water), to yield significant values of mechanical properties such as Hookean modulus, ultimate tenacity, ultimate strain, hysteresis, and permanent set. Effects upon these properties of varying gage length and linear density were studied, and appropriate corrections were made in interpreting the tenacity-strain data.

Tenacity-strain curves for untanned and tanned fiber aggregates indicated the predicted plasticizing effect of sorbed water, which shifted the curves toward the strain axis. Curves for the untanned fiber aggregates exhibited behavior similar to the "uncrimping phenomenon" observed with wool fibers. This was interpreted as a straightening and alignment of the primitive fibers into the direction of tensile stress, at low strains. Tanning appeared to inhibit this process, since tenacity-strain curves from tanned samples did not show this "character" at low strains. At higher strains, however, this apparent inhibition of primitive fiber readjustment was broken down, and rather rapid yield took place. Tanned fiber aggregates were weaker (lower ultimate tenacity) than untanned aggregates in the "dry" state, but not in the wet state. Tanning also appeared to improve the resilience characteristics of the fiber aggregates, as judged by lower values of dissipative properties, such as hysteresis and permanent set, found in strain-cycling experiments.

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## APPENDIX

*Definitions of Textile Terms*

**Gage Length.**—Initial length of that portion of a specimen actually extended in a tensile test.

**Linear Density.**—Mass per unit length of a specimen, often expressed in tex units.

**Tex.**—Mass in grams of a 1-kilometer length of specimen. This is equivalent to micrograms per millimeter.

**Tenacity.**—Tensile load divided by linear density, often expressed as grams per tex.

**Ultimate Tenacity.**—Value of tenacity at which specimen ruptures under tensile load.

**Strain.**—For tensile strains discussed in this paper, extension of fiber per unit gage length.

**Ultimate Strain.**—Strain at rupture.

**Hookean Behavior.**—Behavior yielding a linear tenacity-strain curve.

**Hookean Modulus.**—Slope of the linear portion of the tenacity-strain curve often expressed in grams per tex per unit strain (since strain is dimensionless, this is abbreviated to grams per tex).

**Breaking Length.**—Length of a specimen just sufficient so that specimen will break under its own weight. Breaking length expressed in kilometers is numerically equivalent to ultimate tenacity in grams/tex.

**Hysteresis.**—Energy irreversibly absorbed in one extension-contraction cycle, divided by the energy of extension.

**Extension Work Change.**—The difference in the work of extension of two consecutive extension-contraction cycles, divided by the work of extension of the first cycle.

**Permanent Set.**—Unrecovered strain at the end of an extension-retraction cycle.